**C-17 CENTERLINING – ANALYSIS OF PARATROOPER TRAJECTORY**

GRADUATE RESEARCH PROJECT


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AFIT/GOS/ENS/05-02

**DEPARTMENT OF THE AIR FORCE**
**AIR UNIVERSITY**

# AIR FORCE INSTITUTE OF TECHNOLOGY

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# C-17 CENTERLINING — ANALYSIS OF PARATROOPER TRAJECTORY

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## Abstract

The C-17's widebody design creates concern over its tendency to "centerline" paratroopers as they exit. This effect increases the probability of collision between jumpers from opposite sides of the aircraft. Previous work has been accomplished based on calculating the separation distance between trajectories and creating cumulative distributions of separation distances. This project focuses its analysis on the trajectories and any trends that can be seen over time, based on changing aircraft gross weight. The trajectories are also analyzed for time dependence. In the end, new insight was gained into the behavior of the trajectories and can supplement previous efforts with additional methodology.

## Table of Contents

Page

## List of Figures

Page

## List of Tables

Page

## C-17 CENTERLINING – ANALYSIS OF PARATROOPER TRAJECTORY

### I. Introduction

#### Background

This research project focuses on something called "wide-body centerlining". This describes the aerodynamic flow around the fuselage of an aircraft and its tendency to move towards the longitudinal centerline of the vehicle, once the aircraft has gone by. Figure 1 shows a simplified example of how air flows around the aft section of a C-17 aircraft. Much like the wake of a boat, the fluid has a tendency to flow toward the center, after the vehicle has passed and disrupted the air flow.

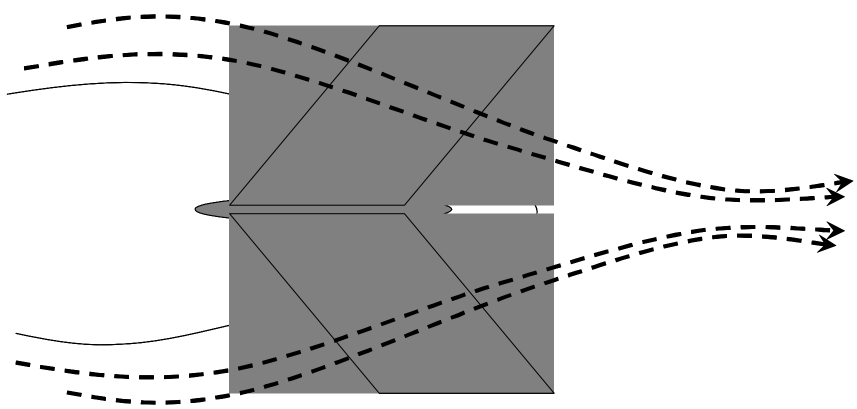


**Figure 1. Centerlining of airflow around fuselage**

Wide-body centerlining tendency is an area of concern for Department of Defense (DoD) personnel with respects to paratroop airdrop and potential mid air collisions/entanglements. Currently, the addition of the C-17 as the preferred platform for mass troop delivery has made US Army and Air Force personnel take notice of this potential danger to the jumpers. As jumpers leave the aircraft, their position is solely determined by those aerodynamic forces immediately surrounding and aft of the fuselage, until their parachutes have inflated and they can assert some form of control of the canopy and their trajectory. Once they do have control, they are trained to gain situational awareness and steer away from possible collisions with other jumpers. During the initial six seconds of the jump, however, the jumper's trajectory will be mostly determined by the forces of the air currents left behind the body and tail of the aircraft. This project's goal is to gain insight into the centerlining tendencies of the C-17, as the engineers attempt to expand the weight envelope of the C-17 paratroop drop configuration, while releasing jumpers from both doors simultaneously.

**Problem Statement**

Engineers from the C-17 System Program Office (SPO) approached AFIT faculty in 1994 to establish the testing protocol and methodology for certifying the C-17 as a safe jump platform. This work was performed by Dr. Kevin Lawson, of the AFIT Department of Mathematics. Follow on work was performed by Maj Wonsik Kim, Republic of Korea, while a Master's degree student at AFIT in 1996. For this work, the primary measure of merit researched was the probability of collision by any two given jumpers. Every jumper's trajectory was compared to all possible opposite door trajectories and a minimum separation was calculated at any point throughout the jump envelope. This created an empirical distribution of minimum separation distances, and cumulative distribution functions were then compared in different configurations (Lawson, 1994). However, there was no individual trend analysis done for the trajectories.

When tasked with expanding the envelope of the C-17 (previously restricted to 360,000 lbs gross weight), flight tests were executed and the same methodology as before was applied. US Army officials, however, were not willing to certify the results and approve expansion of the envelope until they had a better understanding of the centerlining effect on the jumpers. This project concentrates on precisely that; the trend analysis of individual components of position at higher weights of the C-17. Using data from more recent flight tests, the position data is analyzed for tests at 360, 385, and 400 thousand pounds gross aircraft weight. The data is then analyzed for trends, and time dependence. More specifically, how much of a factor is aircraft weight playing on the jumper trajectories? This project has the goal of providing the C-17 SPO engineers with insight into what the increased weights are doing to the jumpers, to better understand and add credibility to their recommendations to certify the expanded envelope.

**Objectives**

Primary Objective: Gain some insight into understanding the effect of weight on aircraft centerlining effect. While the true effect can only be quantified in the wind tunnel, this project hopes to provide the experts with some measure of response for each individual jump, and with respect to time.

Secondary objective: Examine Time dependency between jumps. The original test methodology, assumed that a given jump could be compared to any other opposite door jump, on a one-to-one basis, and consider it a proper pairwise comparison, to obtain a minimum separation distance between the two trajectories.  Is there a significant difference between the first trajectories and the last trajectories?  If weight caused a significant difference in trajectories, should early jumps (heavier) be compared to later jumps (lighter aircraft due to fuel burned)?

In the end, the latest flight test data indicates that the 400K lb configuration of the C-17 should be certified for safe airdrop.  However, this project is not aimed at accomplishing that task, only to aid decision makers in quantifying their certainty that jumpers may proceed safely, with less danger of entanglements.  Even so, fewer entanglements may not be the driving safety issue, if other unintended effects arise from higher weights that may render the airdrop unsafe or impractical for other reasons. Extreme care should be taken when making inferences or conclusions about the true cause of any variations in the data, since the aerodynamic effects of higher weights around the aircraft are not part of this research.

**Research Focus**

For this project, the focus is limited to airdrop of test jumpers or mannequins from a C-17 aircraft at Edwards Air Force Base, CA.  The data available is for three airdrop tests, at 360K, 385K, and 400K lbs gross aircraft weight.  The data consists of cinetheodolyte (CINE T) camera tracking of object center of mass, providing distance from the jump point in three coordinate axes.  The analysis focuses on the individual trajectories and their trend behavior through the flight envelope.  Also, the data will be examined for time dependence, since the aircraft is losing fuel weight during the flight test, and may be causing variations in the trajectories.

## Methodology

The analysis performed, while fairly simple to accomplish, had not been addressed or accomplished during the previous efforts with this data. Each trajectory is a time-stamped sequence of lateral, longitudinal, and vertical position with respect to the aircraft exit point. The mean and variance of the trajectories were then calculated, compared, and plotted against each other for a visual representation of the trends. Analysis of variance (ANOVA) techniques were applied where necessary to verify significant differences between distributions. More specifically, the ANOVA was used to show that the mean position of the left and right trajectories are indeed separate (means are significantly different), since centerlining would tend to bring them together. Also, linear regression was used to study the effects of changing weight during a single test run, by comparing the position data vs. jump number, and showing if a linear relationship exists between heavier weights and position in each direction.

## Assumptions/Limitations

Flight Conditions – All jumps were accomplished at 135 knots true airspeed +/- 5 knots, and 7 degrees deck angle (aircraft angle of attack).

Flight Test Discipline – The flight tests were performed in similar conditions, on different airplanes, and were in no way connected as one test program. This may have led to inconsistencies in the resulting test execution which may not have been accounted for. So far, research has not shown major discrepancies or glaring differences in the conduct of the test on different dates. All tests were conducted under calm winds (at or below 5 knots) and all jumps were performed heading into the wind to minimize crosswind effect on trajectories. It is unclear which flights were done as continuous jumps or with landing and refueling in between.

Jumper Descent Rates – Altitudes are assumed to be equal for all trajectories at equal points in time. Separation distances were calculated using straight line distance formula between the lateral and longitudinal axes, but not the altitude axis. The assumption was made that the jumpers fall at the same rate and there are no other forces in the Z direction (up/down) acting on the body, therefore, differences in the altitude are negligible for the calculations. This analysis later verified this assumption.

Data Integrity – The data consists of over 25,000 data points. The data was reviewed for inconsistencies and irregularities. One jump at 400K was deemed unusable data and was removed from the data set. The trajectory moved erratically, and outside the normal parameters of the other trajectories. This may happen if the CINE T camera cannot track the body and goes into a search mode looking for the mass in its field of view, and may oscillate in a search pattern. Also, some of the data for 400K had to be adjusted to reflect consistent sign convention with the 360K and 385K data. The other data sets used a positive value for right of centerline and negative value for left of centerline. The 400K data had to be reversed to ensure the corresponding jumps were adjusted to the same directional schema.

# II. Initial Work and Data Definitions

## Overview

The purpose of this chapter is to describe in more detail the initial work that was done with respect to this project, and accomplished by members of the AFIT Operational Sciences Department. It is intended to briefly describe some of the methodology employed by this work, to better understand the current measures of merit used in assessing worthiness of an airdrop platform.

## Description

Entanglement between two paratroopers is potential for catastrophe. It is even more dangerous during the initial phases of a static line jump, where the jumper is still moving at a high rate of speed, and the parachute has not yet inflated. The jumper has little control or situational awareness, and any entanglement may prevent chute inflation at all. Possibility of entanglement thus becomes a primary item of interest in ensuring jumper safety.

The previous methodology employed for evaluating C-17 paratroop drop capability, used separation distance between jumpers as its critical data element to perform analysis. The test flights involved the use of test jumpers or mannequins, which were dropped at the rate of one or two per pass, but never at the same time. The aircraft would then fly an entire orbit, and set up for another pass, then release one or two more. The data for each jump consists of XT, YT, and ZT position of the centroid of mass, starting at time 0, updating every 0.05 seconds, and ending somewhere between 6.95 and

9.5 seconds.  Position data is positive for front, right, and up directions from the drop point.  It is negative for aft, left, and down directions from the drop point. Table 1 shows a sample of the data files provided by C-17 SPO.  Each jump was classified by gross weight and door (left or right), and a jump number was assigned for that sequence at a given weight.

**Table 1. Sample Data File**

| TIME | XT | YT | ZT | XC | YC | ZC | XTJ | YJ | ZJ |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 13.543 | -5.40075 | 0 | 14.3097 | -5.2036 | 0 | 12.7763 | -5.5979 |
| 0.05 | 9.4039 | 13.66305 | -5.4437 | 9.3526 | 14.5444 | -5.2464 | 9.4552 | 12.7817 | -5.641 |
| 0.1 | 19.0012 | 14.00645 | -5.4388 | 18.9873 | 14.9543 | -5.2763 | 19.0151 | 13.0586 | -5.6013 |
| 0.15 | 28.8828 | 14.35845 | -5.47055 | 28.9591 | 15.2921 | -5.322 | 28.8065 | 13.4248 | -5.6191 |
| 0.2 | 38.98995 | 14.50705 | -5.5662 | 39.2197 | 15.3635 | -5.3987 | 38.7602 | 13.6506 | -5.7337 |
| 0.25 | 49.1106 | 14.40465 | -5.7233 | 49.593 | 15.1779 | -5.5357 | 48.6282 | 13.6314 | -5.9109 |
| 0.3 | 58.9862 | 14.1696 | -5.9654 | 59.8278 | 14.9054 | -5.7774 | 58.1446 | 13.4338 | -6.1534 |
| 0.35 | 68.46976 | 13.9736 | -6.28925 | 69.7197 | 14.7209 | -6.1275 | 67.2198 | 13.2263 | -6.451 |
| 0.4 | 77.59351 | 13.95495 | -6.6219 | 79.2065 | 14.7259 | -6.4964 | 75.98051 | 13.184 | -6.7474 |
| 0.45 | 86.53235 | 14.15015 | -6.9039 | 88.37659 | 14.9288 | -6.7625 | 84.6881 | 13.3715 | -7.0453 |
| 0.5 | 95.49965 | 14.4696 | -7.1544 | 97.3876 | 15.2377 | -6.9216 | 93.6117 | 13.7015 | -7.3872 |
| *Data* | *Continues* | *To* | *7 seconds* | … | … | … | … | … | … |

NOTE: While the data contains specific tracking for the jumper center of mass and the canopy center of mass (XTJ, and XC), the analysis presented here is done using XT, which is a weighed value between the jumper and the canopy.

**Minimum Separation Distance**

The initial work performed by Dr Lawson and Maj Kim revolved around the minimum separation distance.  For each jump within a weight category, each jump was compared to all jumps from the opposite door.  For example, if jump #1 was from the left door, then it was paired with all jumps from the right door like jump#2, jump#4, and jump #6…etc.  The assumption is that any given jump from the left side is equally likely to be paired with any of the right side jumps and vice-versa.  After being paired, a separation distance is calculated between the jumpers using a basic distance formula (Lawson, 1994):

$$d_t = \sqrt{(x_t)^2 + (y_t)^2}$$

Where,
$x_t$ = position in the longitudinal direction form jump point at time t
$y_t$ = position in the lateral direction from jump point at time t

For the given jump pairing (i.e. jump#1 with jump#2), a separation distance $d_t$ is calculated for each time interval (i.e. 0 sec, 0.05 sec, 0.1 sec… etc). This provides one sample for minimum separation, by using the smallest separation calculated ($D_{min}$= min{$d_t$}) for all $t$ in that trajectory. Then pairings continue for jump#1 (left door) with the remaining even numbered jumps (right door), providing one sample of minimum separation distance for each pairing. Assuming $n$ total jumps, and equal number of left and right side jumps, this yields $n/2$ samples based on jump#1. The same procedure is accomplished for all odd numbered jumps, each yielding $n/2$ samples, for a total of $(n/2)^2$ samples. Finally, for any given weight configuration, there exists an empirical data set of minimum separation distances consisting of $(n/2)^2$ samples. These data sets become the sources for the individual cumulative distribution functions (CDF) used when comparing different configurations of airdrop platforms. In the past, the comparison of these CDFs has been the foundation for deciding if it is safe to expand the envelope. Table 2 in Chapter III shows the individual sample sizes for this project.

**Comparing CDFs**

Figure 2 below, shows an example of the previous calculated comparisons between C-141s and C-17s. The graph was extracted from Maj Kim's AFIT Thesis, Personnel Airdrop Risk Assessment, 1996. The traces in the graph represent: (1) a C-141 at 330K, (2) a C-17 at 330K, (3) a C-17 at 360K and (4) a C-17 at 380K.

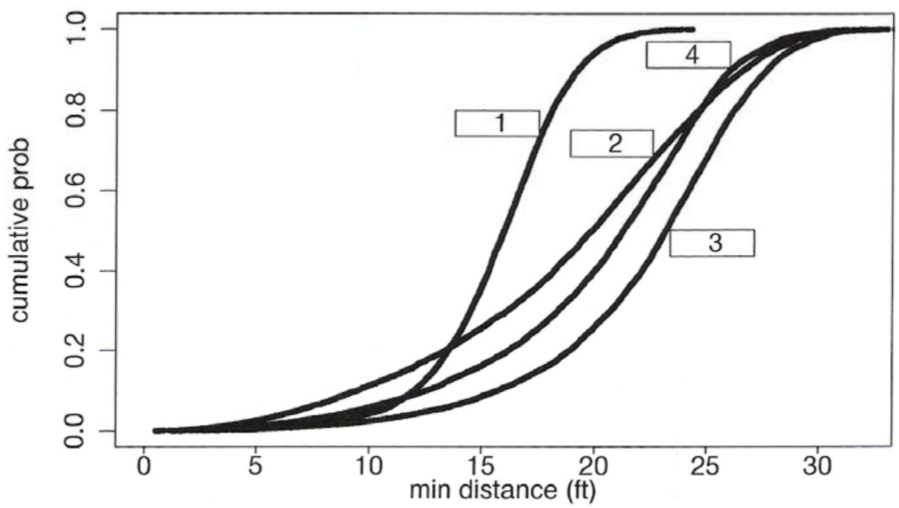



**Figure 2. Minimum Separation CDFs of C-141 and C-17**

Note that all C-17 traces appear to dominate the C-141 trace, though not throughout the envelope. From this graphic, the report concluded that trace # 3, a C-17 at 360K pounds provided the safest conditions because it yielded lower probabilities of occurrence for all minimum separation values (Kim, 1996).

Figure 3 below, comes from the recent briefing by the C-17 SPO to the US Army Aviation R&D Engineering Center (Kuntavanish, 2004). It shows the CDF comparison for the recent test jumps which included jumps at 400K.

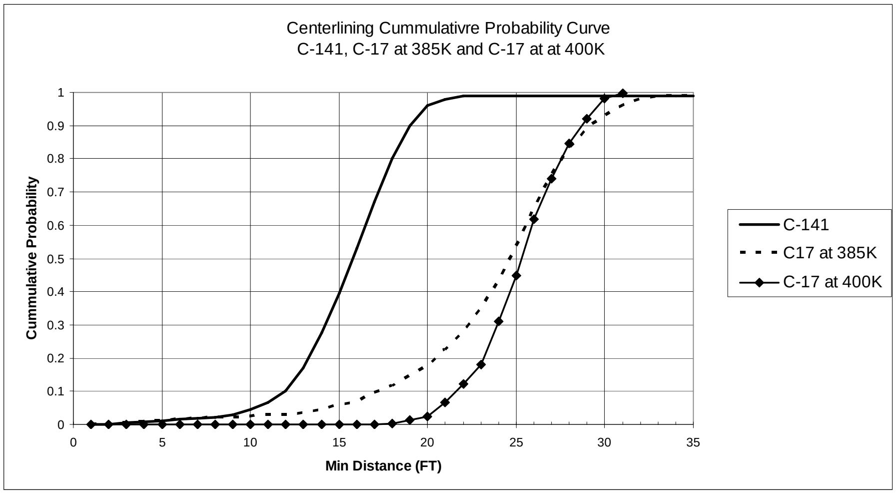



**Figure 3. Minimum Separation CDFs of recent C-17s**

Note the large increase represented by the distance between the C-141 curve and the C-17 curves. This represents a substantial decrease in the probabilities for smaller minimum separation distances. C-17 SPO personnel interpret this as a vast improvement in collision avoidance which provides sufficient justification to certify weights up to 400K lbs as a safe jump configuration. Also, note the decreased probabilities between 385K and 400K, and when compared to the 360K CDF in Figure 2, 400K shows a major improvement in probabilities. For example, the probability of a minimum separation distance of 25 ft (commonly considered as the critical distance at which a collision occurs) decreases from about 0.7 at 360K to 0.45 at 400K. These are arguably some very significant differences that are going unexplained. Furthermore, there is no insight into when in the envelope these minimum distances happened. There is knowledge to be gained from understanding at what point in the trajectory the distances happened. Early in the envelope (up to four seconds), jumpers have no control, but later in the trajectory, as the chute inflates, there may be actions the jumper can take to help deconflict.

**Critical trajectory points.**

C-17 SPO personnel expressed particular interest in the data behaviors at 4 seconds and 6.5 seconds. The 4 second point is of interest because it is the point where a jumper canopy begins inflating, and the jumper begins to decelerate and swing down from a sideways position after entering the aircraft. At 6.5 seconds, the jumper is considered to have achieved “first vertical” and is assumed to be able to gain some form of control of the canopy. While there were no specific criteria to be looked at, they were interested in the behavior of the position data at those specific points, with the hopes to gain some clue as to the degree of collision risks at those points.

## Summary

In the end, there are still unanswered questions about the true nature of the centerlining tendency. None of the literature and research showed any studies dedicated to the aerodynamic effects around the fuselage of the aircraft (i.e. laminar flow analysis, wind tunnel testing). Clearly, calculating probabilities of collision remains the most quantitative assessment with regards to overall safety of the jumpers, but it still does not provide the full picture. Fewer or less frequent collisions indicates better separation between jumpers, but without understanding the cause of this separation, jumpers could be in danger from other unexplained forces. It begs the question: why was there such a vast improvement in collisions when common sense dictates that the centerlining should be more severe? This analysis hopes to provide some support to follow on avenues of research to better understand this phenomenon.

# III. Methodology

## Overview

The purpose of this chapter is to outline the analysis methodology used for this project. Each trajectory is a time-stamped sequence of lateral, longitudinal, and vertical position with respect to the aircraft exit point. The analysis is attempting to characterize the position data with respect to time from jump point to loss of data (usually six to nine seconds after jump). The mean and variance of the trajectories were calculated, compared, and plotted against each other for a visual representation of the trends. ANOVA was used to show that the mean position of the left and right trajectories are indeed separate (means are significantly different), since the centerlining effect would tend to bring them together. Also, linear regression was used to study the effects of changing weight during a single test run, by comparing the position data vs. jump number, and showing if a linear relationship exists between heavier weights and position in each direction. Most of the analysis was accomplished using Microsoft® Excel and JMP v 5.1.

## Data Organization

Data was provided by the C-17 SPO for three flight tests: 360K, 385K, and 400K. Table 2 shows the number of jumps for which data is included in the analysis. After the data was studied and adjusted, some jumps were removed or reclassified as left or right jumps based on inconsistent data production from the test execution. Each flight test had a different number of jumps because they were all done as part of other efforts and consistent sample size was not seen as a critical issue at the time. The tests also have different numbers of left and right jumpers.

**Table 2. Sample sizes for jump conditions**

| DOOR | 360K | 385K | 400K |
|---|---|---|---|
| Left | 20 | 34 | 32 |
| Right | 20 | 38 | 30 |
| Total | 40 | 72 | 62 |
| CDF Sample Size | 400 | 1296 | 961 |

**Position Trend Analysis**

The first area of interest is to identify any trends that may exist in the particular trajectories. This assessment is accomplished by comparing the distributions of the position data, at a given point in time, and comparing across different gross weights. Often, looking at the data in an aggregate manner can reveal a lot about the set as a whole. This "big picture" approach can reveal those potential areas of conflict, or where data is missing, erroneous, or outlying. This is akin to the exploratory data analysis suggested as the first step in most linear regression strategies, when little is known about the data (Kutner, 2004). In this case scatter plots and sequence plots are the main tool used in this visualization. As an example, Figure 4 shows a scatterplot of the trajectories. Each trace represents a series of values for position from "time zero" until the end of the tracking (usually 6-8 sec), at intervals of 0.05 seconds. This plot clearly demonstrates that one trajectory contained bad data and should be removed from the data set.  It shows a trajectory moving straight to the right, without descending.

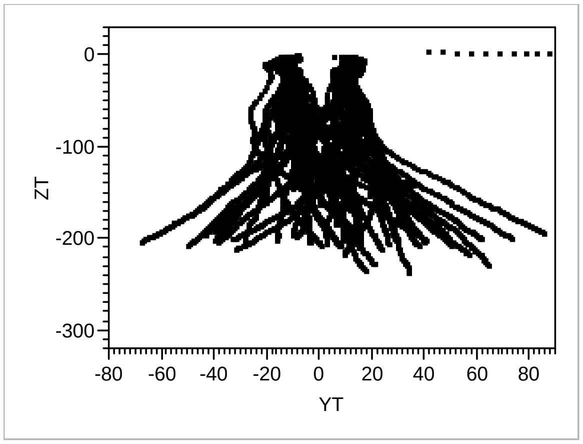



**Figure 4.  Example of Bad Data at 400K.**

Once the sanity check was complete, and bad data removed, the analysis continued.  Individually, the longitudinal (XT), lateral (YT), and vertical (ZT) components of position were studied.  Means and standard deviations of position at each given time increment were calculated and graphed for comparison.

**Measures of Merit**

Mean position – For each weight configuration, the mean position was calculated for both left and right side jumpers separately, at each time step.

Standard Deviation – For each weight configuration, the standard deviation was calculated for both left and right side jumpers separately, at each time step.

Distribution parameters – The distribution of position values were characterized at 4 and 6.5 seconds in all three directions.  At each time, the means and standard deviations were calculated, as well as the 95% confidence intervals (CI).

There are no evaluation criteria identified for this analysis. The comparison is accomplished for research purposes only.

**Time Dependence Analysis**

This analysis focuses on the assertion that any given jump is equally likely to pair up with all jumps from the opposite side. The intent is to investigate how, within a single weight configuration, time might affect the position of the jumper. More specifically, this determines if there is any dependence between position and jump number. Sequence plots are used as the tool to show if there is a significant linear relationship.

**Measures of Merit**

P-value of linear fit – A linear regression fit will be made from the position data at a given time interval. The P-value indicates the confidence that a statistically significant linear relation does indeed exist. It is actually the probability that we would be incorrect if we assumed a linear relationship exists. A small P-value means a small probability of incorrectly assuming a linear relationship. In the context of the previous analysis, it means it may not be appropriate to compare early jumps to late jumps because something is causing the position data to increase or decrease with time. A P-value smaller than 0.05 indicates better than 95% confidence that our assertion is correct (Devore, 2004).

**Summary**

The methodology is fairly simple. Typical strategies for linear regression require that exploratory data analysis be accomplished prior to making the assumptions necessary to continue.  This project focuses on such exploratory analysis of the position data, trends that may be inherent, and any relationships with respect to time.

Here is one final note on the subject of methodology.  Once the analysis was accomplished, the results were compiled, but no conclusions are included in this report. While this analysis can characterize the behavior of the position data, no direct conclusion can be drawn as to the cause of these results.  There is no data with respect to what kind of aerodynamic behavior is being exhibited by the laminar flows and turbulence that surround the fuselage and tail as it passes through the air and the jumpers fall aft.  It is reasonable to surmise that a heavier airplane will cause different aerodynamic flows due to increased drag and different flap settings (required to maintain the same airspeed and deck angle for all jumps), but there is no data quantifying what those aerodynamic forces are and in what direction.  This report goes directly from results to recommendations.

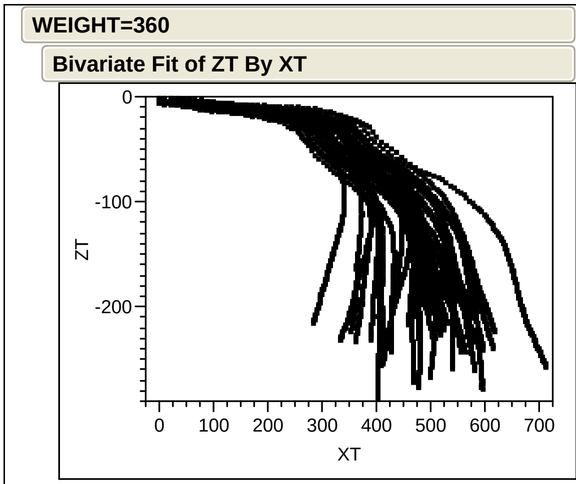
## IV. Analysis and Results

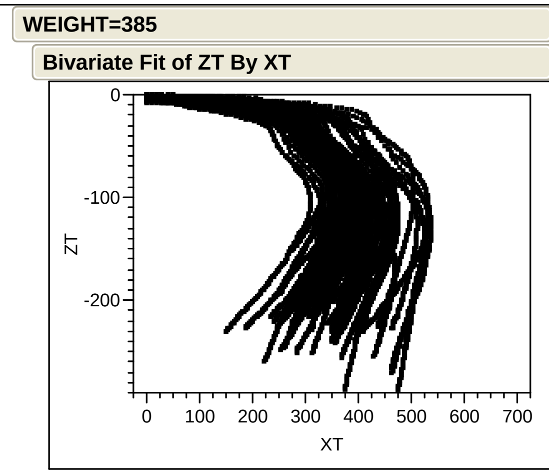
### Overview

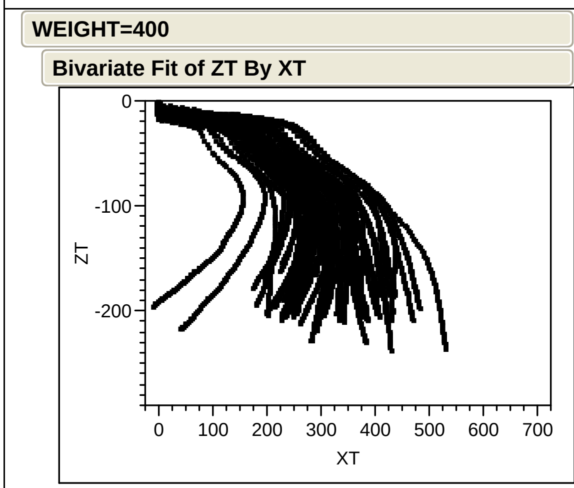
The presentation of the results mostly consists of graphical visualizations of the calculated measures of merit. Scatterplots and line charts suffice to demonstrate the trends and differences between jump conditions and configurations. The analysis is restricted to the first seven seconds. Any data trends beyond seven seconds should be considered unreliable due to lack of samples or inconsistent data at times higher than seven seconds. ANOVA was performed on position data in all three directions at 4 and 6.5 seconds to see separation at the critical points. Finally, linear regression was used to test if time is a significant factor in data behavior by looking for linear relationship between jump order and distance traveled.

### Position Trend Analysis and Results

Longitudinal Position ($X_t$) – This is the position along the long axis of the aircraft aligned with aircraft heading at the time of the jump. Figure 5 shows the trajectories of $X_t$ vs. $Z_t$ (altitude). Each graph consists of the "side view" of all jumps as the aircraft moves from left to right. The $Z_t$ direction anchors the jump altitude as the zero value, and the data represents decrease in altitude from zero.




Remarks: Aircraft travels left to right. Initial look at the data suggest that longitudinal distance is decreasing as weight is increasing. The variance is also greater at the higher weights. This shows jumps from both doors.

**Figure 5. Longitudinal position scatterplot "Side View"**

The initial look suggests a trend of decreasing longitudinal distance form the jump point at heavier configurations. It is apparent that jumps from heavier aircraft yield shorter jump distances. Figure 6 verifies this, as it shows the trend for $\overline{X}_t$, the average position at time *t*, classified by door and weight. Figure 7 shows, as expected, that the variability of the position data increases over time as forces other than the airflow affect position.

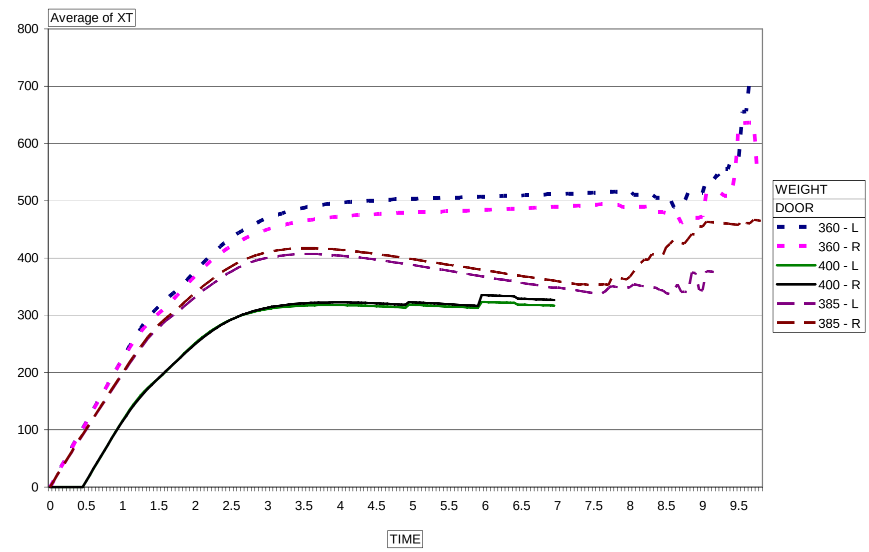



**Figure 6. Mean trends for Xt**

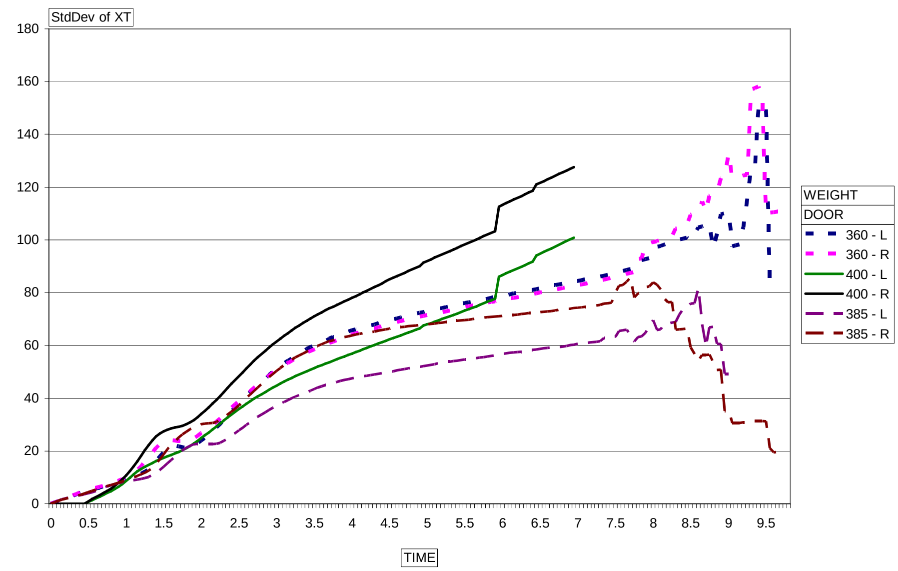
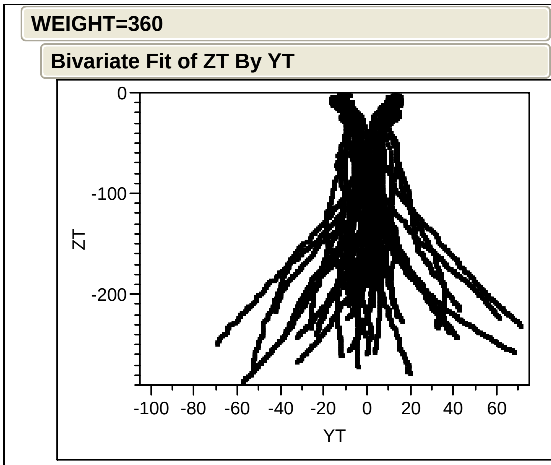
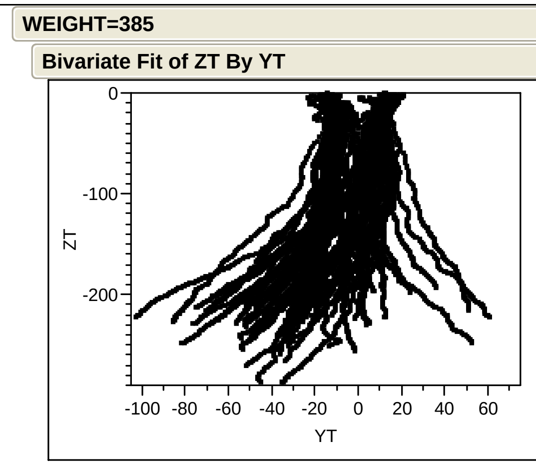


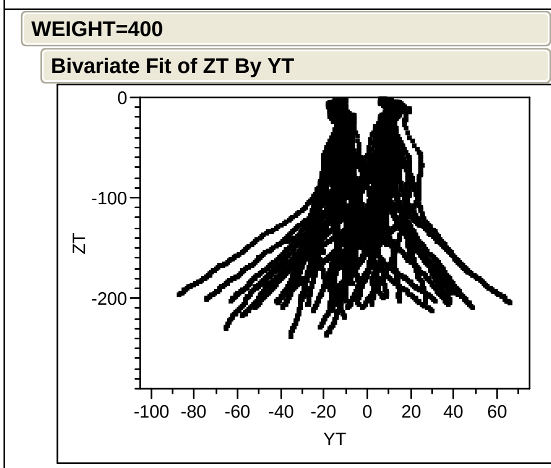

**Figure 7. Standard deviation trends for Xt**

For the 400K data, no data was available prior to the 0.5 second point and therefore, the mean could only be calculated starting one half second later. This graph clearly demonstrates a significant difference in position exhibited at the different weights and emphasizes our initial assertion that heavier aircraft tend to lead to shorter longitudinal distances. The variance, however, did not show a consistent increase with weight and does not show any particular trend other than a steady increase with time. This is expected because later in time, other elements and random effects begin to influence position and cause wider variances, as opposed to early in the jump, where impact with the slipstream around the fuselage is the main force.

Lateral Position ($Y_t$) – This is the position along the lateral axis of the aircraft aligned perpendicular to the aircraft heading at the time of the jump, with positive values to the right and negative values to the left of centerline. Figure 8 shows the trajectories of $Y_t$ vs. $Z_t$ (altitude). Each graph consists of the "front view" of all jumps as the aircraft moves "into the paper". Figure 9 shows $Y_t$ vs. $X_t$, providing the "Bird's eye view" of the jumps as the aircraft travels from left to right.

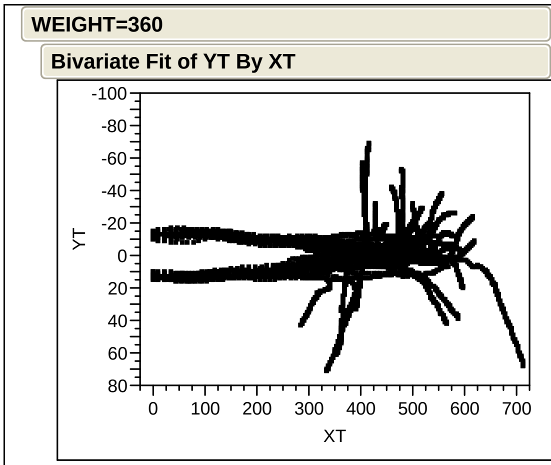


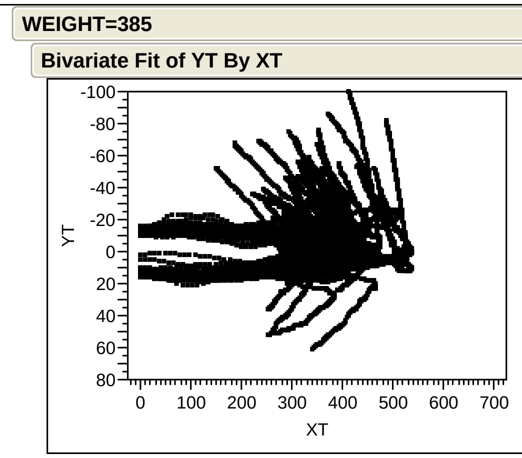



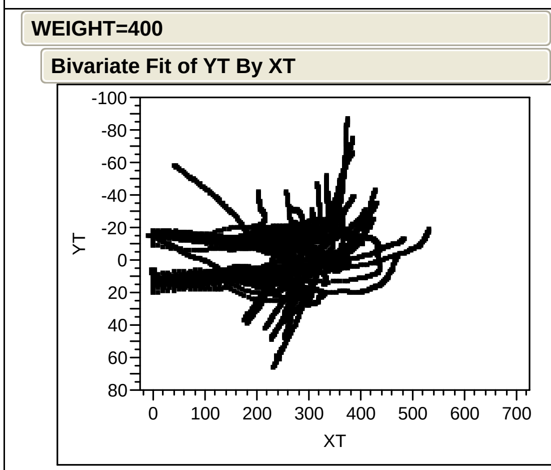




Remarks: Aircraft travels into the paper. Initial look at the data suggest that while jumps at 360K seem to distribute symmetrically about the center point, jumps at 385K and 400K may be showing a bias towards the left of centerline.

**Figure 8. Lateral position scatterplots "Front View"**




Remarks: Aircraft is flying from left to right. Reinforces previous observation that heavier drops yield shorter distances and the tendency to push the jumpers left of centerline. NOTE: at 400K there is one trajectory that appears to start to the left then cross over across the white void. This is actually a right side jump that follows along with the other trajectories but later gets turned around and travels toward the left side.

**Figure 9. Lateral position scatterplots "Bird's Eye View"**

The scatterplots have yielded some suspicions which need further examination using the sequence plots to study the behavior of $Y_t$. Figures 10 through 13 are the time series plots that reveal the trends for $\overline{Y}_t$, the average lateral position at time *t*, classified by door and weight. It is worthwhile to show them individually for each weight and then in a combined graph. Most noticeable is the fact that the 360K test exhibited an example of perfect symmetrical centerlining (see Figure 10), where a jumper will come out of the door, cross the centerline at about 4 seconds, and continue further toward the opposite side from where they exited.

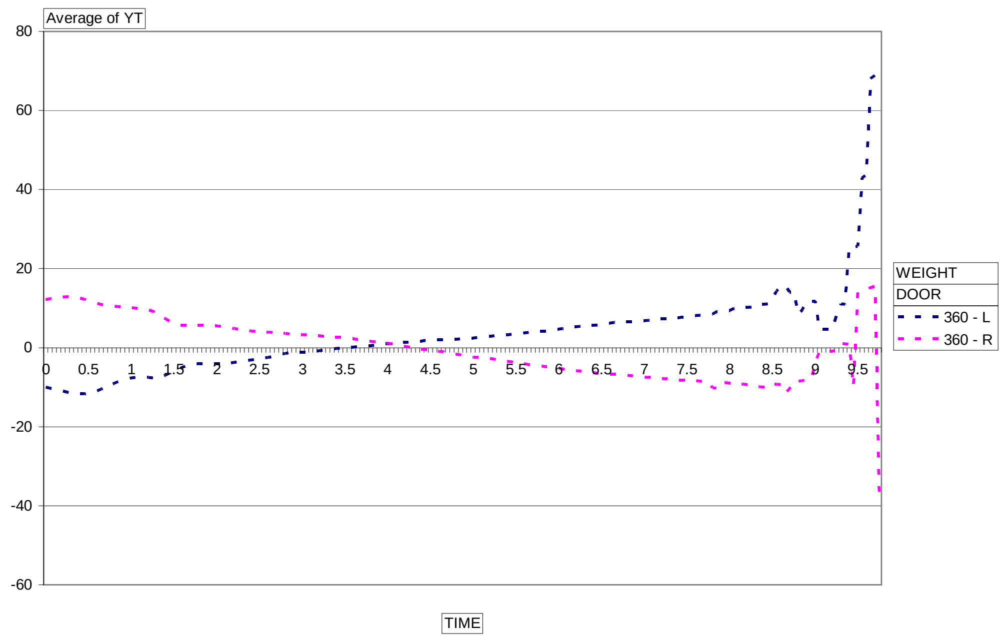



**Figure 10. Mean trend for Yt at 360K.**

This is an undesirable condition because it virtually guarantees any given jumper will probably cross that centerline, thus increasing the chance of entanglement. But for 400K and 385K (Figures 11 and 12), we see a definite trend to push the jumpers to the left of centerline, where right side jumpers come across the centerline, but the left side jumpers continue to the left, maintaining distance from their right door counterparts. At 385K they appear to converge slightly later in the envelope, but at this point, other forces, including canopy control, can become a factor in deconfliction. The 400K jumpers seem to maintain that separation throughout the seven second envelope.

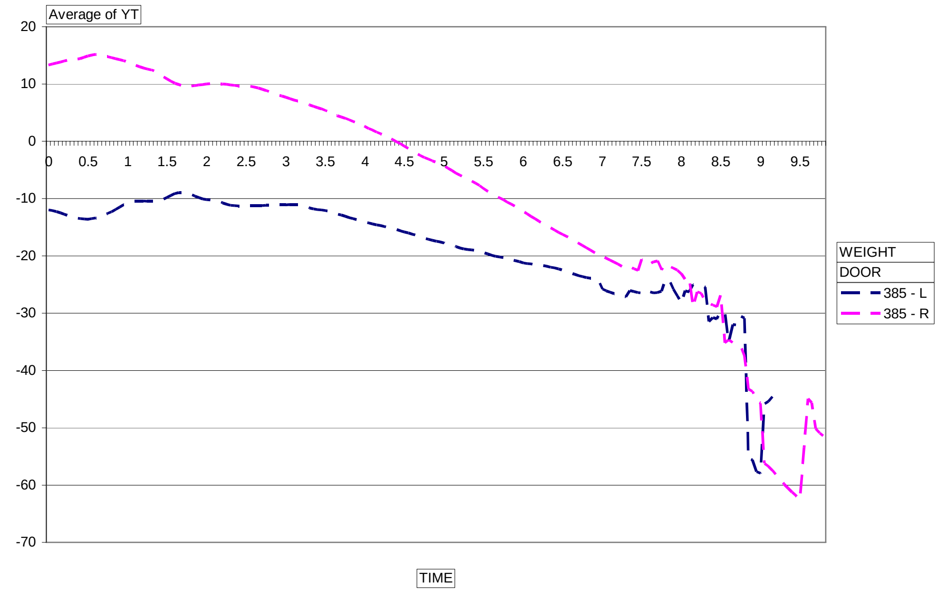



**Figure 11. Mean trend for Yt at 385K.**

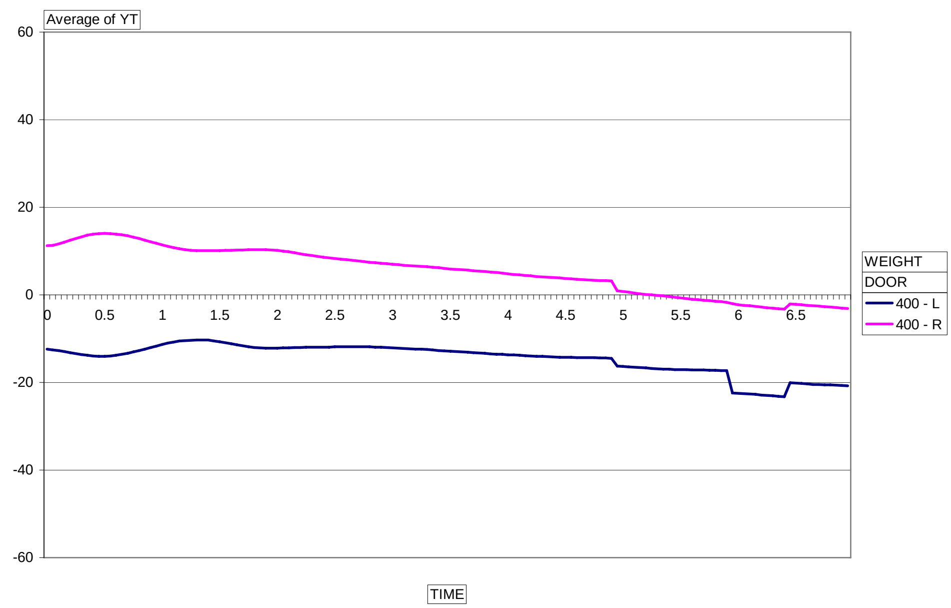



**Figure 12. Mean trend for Yt at 400K.**

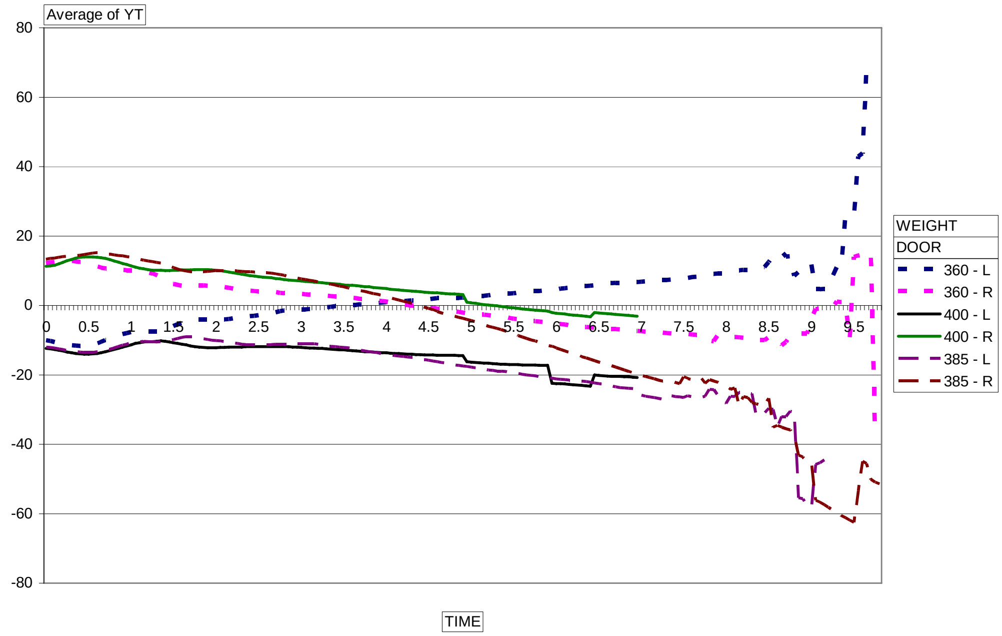



**Figure 13. Mean trends for Yt combined.**

This certainly explains the large improvements witnessed when comparing the CDFs. This yields fewer close calls between jumpers and less likelihood of an entanglement. While it is good news that the heavier configurations yield less centerlining, care should be taken before solely relying on this data in certifying safe jump parameters. It may be undesirable to have a left bias in the lateral direction if you are mass airdropping in formation, or if there is a need for accurately assessing the jumper's probable landing point. Although we have fewer collisions, or rather a lower probability of small separation distances, this left bias may still cause other unsafe conditions which subject matter experts should observe and evaluate.

Figure 14 shows the standard deviation trend for $Y_t$. It shows, like before, the tendency to see larger variances at higher weights and increasing over time, but no other insights are derived from this.

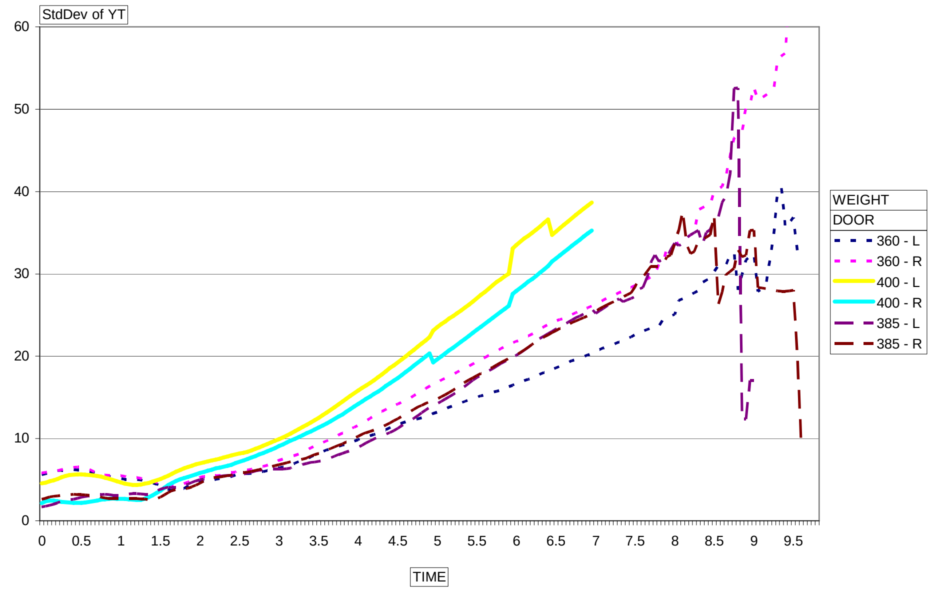



**Figure 14. Standard Deviation trend for Yt.**

Vertical Position ($Z_t$) – Also known as altitude, it's the distance along the vertical axis of the aircraft, pointing at the ground, at the time of the jump. The two previous scatterplots show altitude behavior, but little can be inferred from those. Figures 15 and 16 show the trends for the mean and standard deviation of the vertical position.

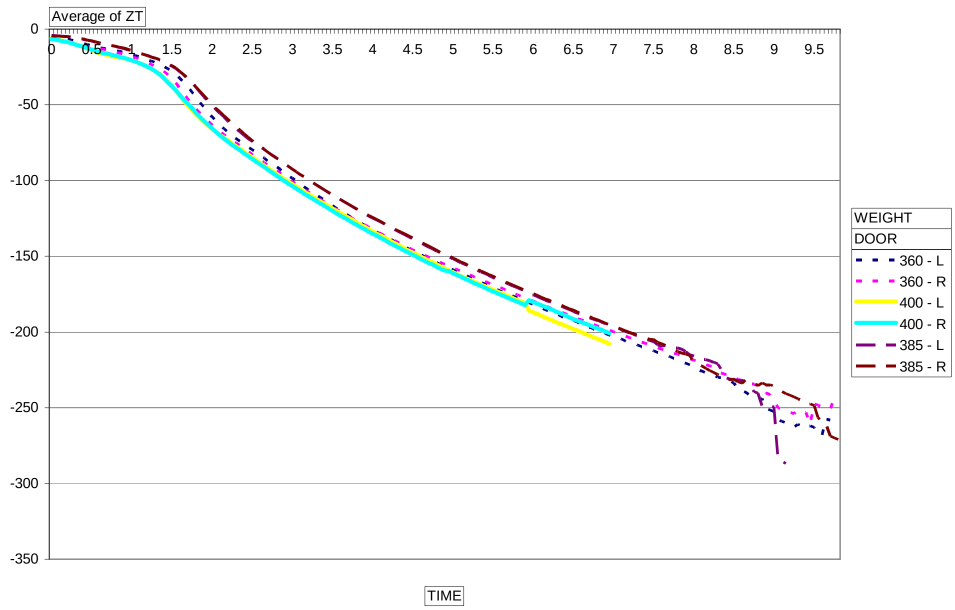



**Figure 15. Mean trend for Zt.**

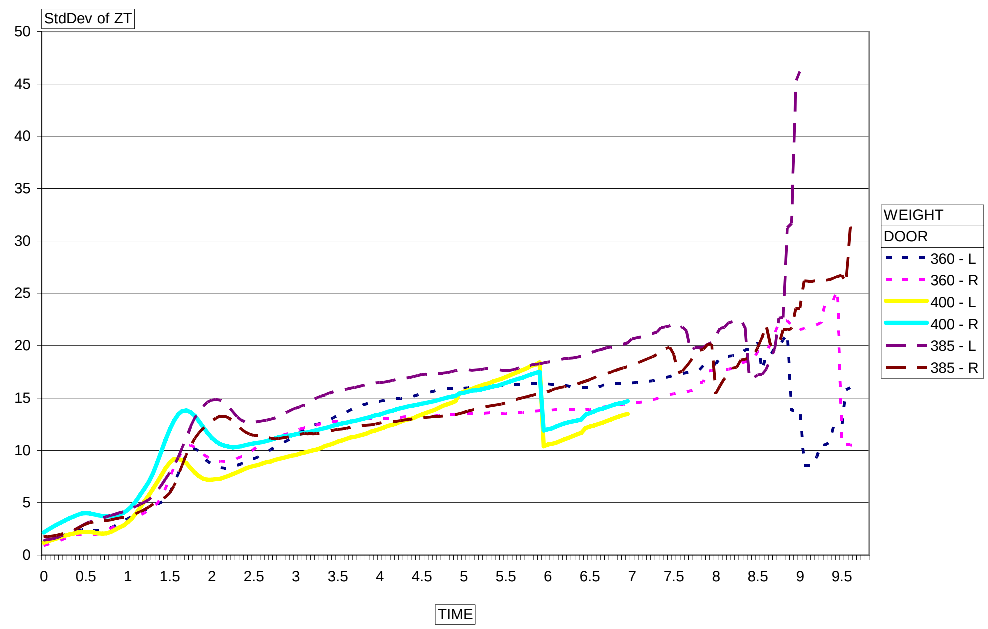
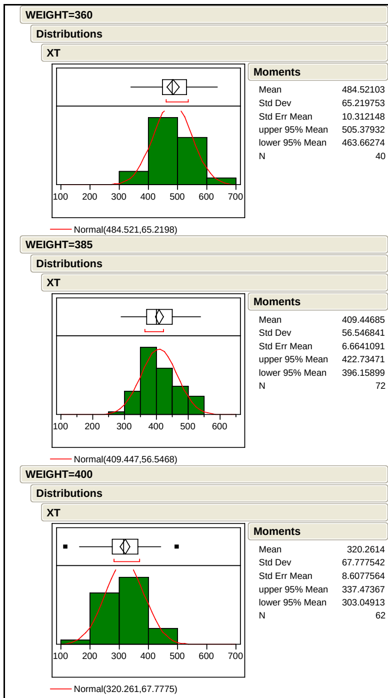
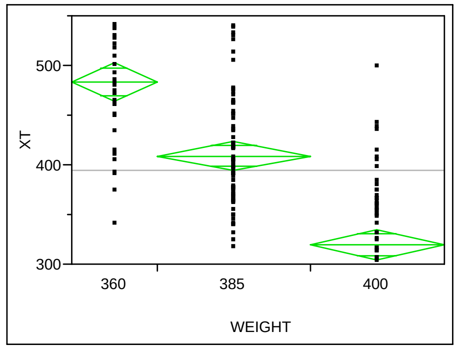



**Figure 16. Mean and standard deviation trends for Zt.**

This particular view of the data reinforces the original assumption that there are no vertical forces other than gravity being exerted on the jumpers. This is shown by how all the traces track so closely with each other regardless of door or even weight configuration. Whatever forces are causing lateral and longitudinal trends, are not causing any bias in vertical position. This finding supports the assumptions made during the original analysis that vertical position could be neglected and all jumper pairings were assumed to be at the same altitude within a corresponding paired time interval (See Chapter I, Assumptions).

Distribution Parameters – The distributions for longitudinal and lateral position were compared at 4 seconds and 6.5 seconds. Based on the previous analysis, vertical position will no longer be analyzed since we expect to see no differences. Figure 17 shows the histograms with fitted distributions and the parameters corresponding to the distribution, along with the 95% CIs of the calculated mean at the 4 second point for all configuration weights. For longitudinal direction, no distinction was made between left and right doors.




**Means for Oneway Anova**

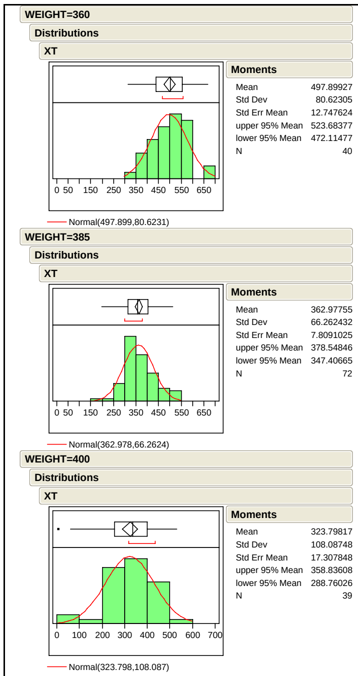
| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|---|---|---|---|---|---|
| 360 | 40 | 484.521 | 9.9203 | 464.94 | 504.10 |
| 385 | 72 | 409.447 | 7.3941 | 394.85 | 424.04 |
| 400 | 62 | 320.261 | 7.9682 | 304.53 | 335.99 |

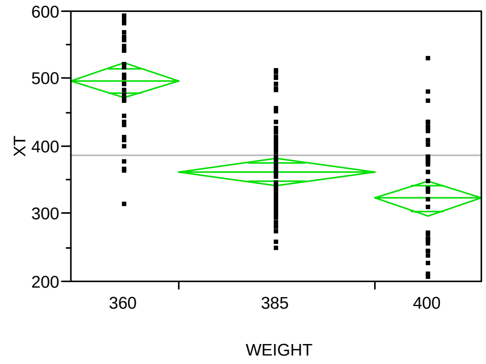
Std Error uses a pooled estimate of error variance

Remarks: The ANOVA graph visualizes the distributions using the diamonds, indicating the mean in the middle, and the 95% CI as the points of the diamond.

**Figure 17. Distribution and ANOVA table of Xt at 4 seconds**

Standard analysis of variance techniques were used to compare means. As a rule of thumb, one can use the 95% CIs given in Figure 17 as brackets to compare to the other two means. For example, the mean at 360K of 484 is bracketed by 504 and 564 as the 95% confidence interval limits. As long as the bracket does not overlap with the 385K bracket between 494 and 424, there is statistical certainty (at the 95% level) that the means are significantly different (Devore, 1994). This technique is applied between all the means. Figure 18 shows the same comparison for the 6.5 second point.




**Means for Oneway Anova**

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|---|---|---|---|---|---|
| 360 | 40 | 497.899 | 13.056 | 472.10 | 523.70 |
| 385 | 72 | 362.978 | 9.732 | 343.75 | 382.21 |
| 400 | 39 | 323.798 | 13.223 | 297.67 | 349.93 |

Std Error uses a pooled estimate of error variance

Remarks: At the 6.5 second point the means do appear significantly different. There is a very small overlap between the interval for 385K and 400K, which may indicate the means are not statistically different.

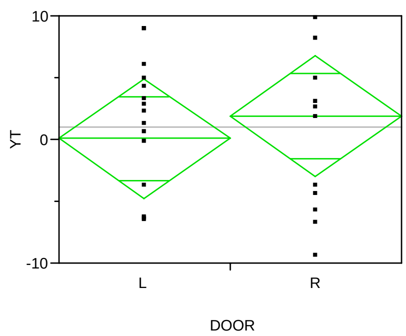
**Figure 18. Distribution and ANOVA table of Xt at 6.5 seconds**

At 6.5 seconds, the separation between the means is clear for 360K, however, the intervals for 385K and 400K do overlap, indicating their difference may not be statistically significant. This is the point where some judgment by the analyst may be useful. At this point we have seen consistent evidence of the decrease in longitudinal distance as weight increases, and the current overlap between the two intervals is very small (approximately 6%). If the confidence interval were changed to 93% vs. 95%, the intervals would no longer overlap. In this case, we will accept the hypothesis that the means for 385K and 400K are significantly different in spite of the current analysis results.

Analysis for the lateral position, $Y_t$, has to be classified by door as well as weight in order to detect any bias caused by the different sides of the aircraft. Figure 19 shows the fitted distributions and the parameters corresponding to the distribution, along with the 95% CIs of the calculated mean by door at the 4 second point for all configuration weights. This analysis did not compare the means across weights; instead it focuses on the left and right doors and the means between the two trajectories to get an idea about the likelihood of a collision at that point. Also, the individual distributions are not displayed since there was no value added to the analysis that is not already apparent from the ANOVA charts.

The results are consistent with what we saw on the trend plot in Figure 13. At 360K the jumpers from opposite doors come together and the distributions are practically identical. Contrast this result to 385K where the mean distance between jumpers is approximately 16 feet and 400K where the mean distance between jumpers is approximately 20 ft. Figure 20 represents the ANOVA tables for 6.5 seconds.

360,000 lb

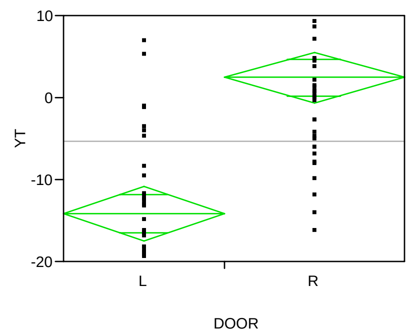



**Means for Oneway Anova**

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|---|---|---|---|---|---|
| L | 20 | 0.12071 | 2.3973 | -4.732 | 4.9738 |
| R | 20 | 1.92600 | 2.3973 | -2.927 | 6.7791 |

Std Error uses a pooled estimate of error variance

385,000 lb

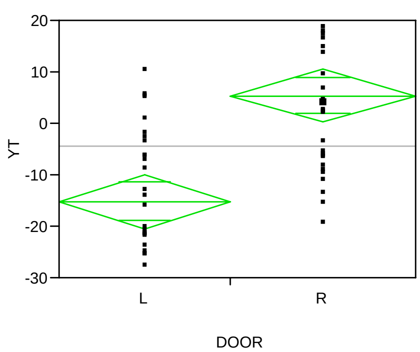



**Means for Oneway Anova**

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|---|---|---|---|---|---|
| L | 34 | -14.048 | 1.6554 | -17.35 | -10.75 |
| R | 38 | 2.535 | 1.5658 | -0.59 | 5.66 |

Std Error uses a pooled estimate of error variance

400,000 lb




**Means for Oneway Anova**

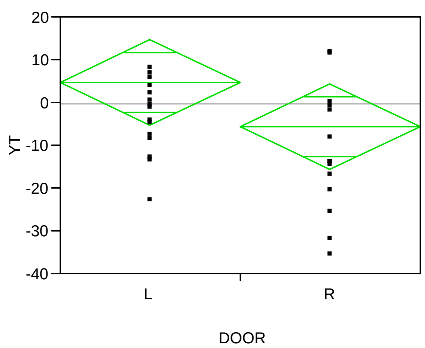
| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|---|---|---|---|---|---|
| L | 30 | -15.057 | 2.6143 | -20.29 | -9.83 |
| R | 32 | 5.533 | 2.5313 | 0.47 | 10.60 |

Std Error uses a pooled estimate of error variance

REMARKS: ANOVA Graphs use the green diamond shape to represent the separate distributions. The center line of the diamond indicates the mean, while the top and bottom ends represent the 95% CI around the mean.

**Figure 19. ANOVA tables of Yt at 4 seconds**

360,000

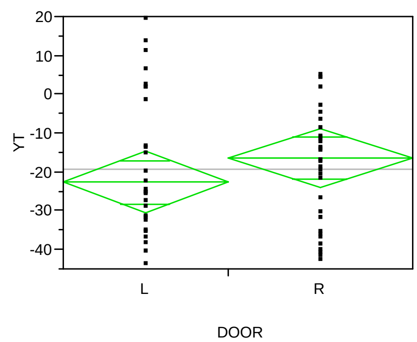



**Means for Oneway Anova**

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|---|---|---|---|---|---|
| L | 20 | 4.7774 | 4.9002 | -5.14 | 14.697 |
| R | 20 | -5.4141 | 4.9002 | -15.33 | 4.506 |

Std Error uses a pooled estimate of error variance

385,000

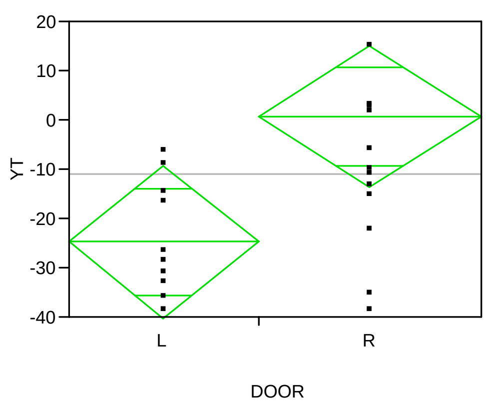



**Means for Oneway Anova**

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|---|---|---|---|---|---|
| L | 34 | -22.499 | 3.9749 | -30.43 | -14.57 |
| R | 38 | -16.280 | 3.7598 | -23.78 | -8.78 |

Std Error uses a pooled estimate of error variance

400,000




**Means for Oneway Anova**

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|---|---|---|---|---|---|
| L | 18 | -24.612 | 7.5955 | -40.00 | -9.22 |
| R | 21 | 0.776 | 7.0321 | -13.47 | 15.02 |

Std Error uses a pooled estimate of error variance

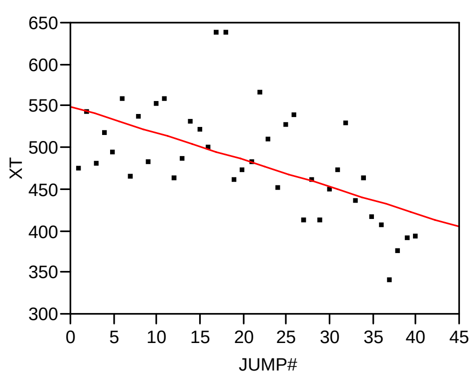
Remarks: ANOVA Graphs use the green diamond shape to represent the separate distributions. The center line of the diamond indicates the mean, while the top and bottom ends represent the 95% CI around the mean.

**Figure 20. ANOVA tables of Yt at 6.5 seconds**

At 6.5 seconds, the jumper has achieved a vertical position and the canopy should be inflated. Other forces, at this point will be affecting the trajectory, and create larger variances within the position data. It confirms what we saw the trend plots in Figure 13, where there was some separation between jumpers at 360K and 385K, but the difference was much less than the separation at 400K. Furthermore, the increase in variance makes the 95% CIs for the means much bigger and makes it more likely that the distributions will overlap. In Figure 20, we see that indeed the difference in means is not statistically significant for any of the weights, but 400K still has a difference in means of over 20 feet.

## Time Dependence Analysis and Results

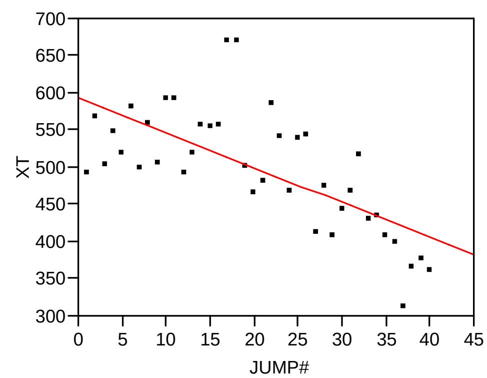
**4 Sec**




**Analysis of Variance**

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Model | 1 | 55598.20 | 55598.2 | 19.1557 |
| Error | 38 | 110292.83 | 2902.4 | Prob > F |
| C. Total | 39 | 165891.03 | | <.0001 |

**6.5 Sec**




**Analysis of Variance**

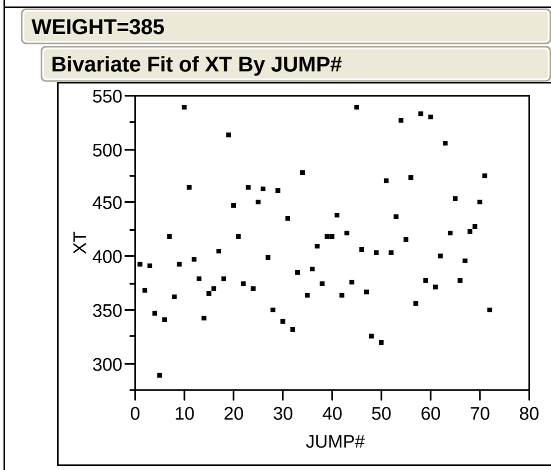
| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Model | 1 | 115936.39 | 115936 | 32.0251 |
| Error | 38 | 137566.58 | 3620 | Prob > F |
| C. Total | 39 | 253502.97 | | <.0001 |

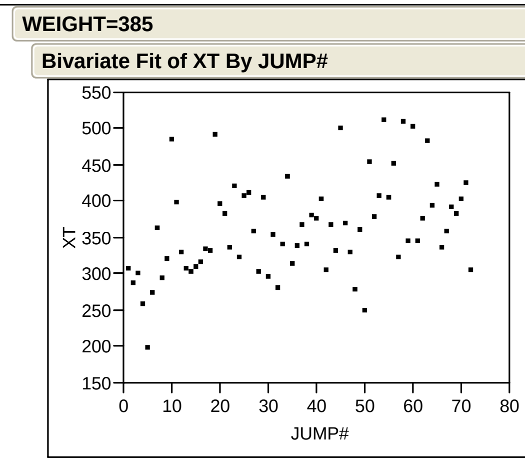
**Figure 21. Sequence plots for Xt at 360K**

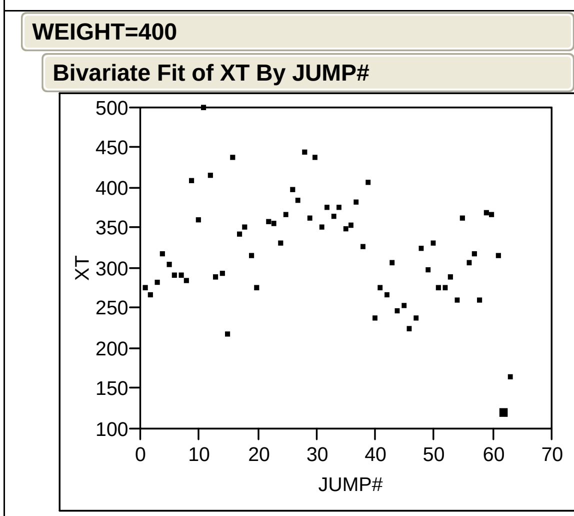
Time dependence analysis focused on determining if a time bias exists in the position data. An aircraft will burn close to 30,000 lbs of fuel while making multiple passes and dropping two jumpers at once for a total of 40 jumps. Jump order has a direct link to aircraft weight since early jumps are made from a heavier aircraft, and the early analysis has shown tendency for heavier aircraft to cause shorter drops. Figures 21 and 22 show the sequence plots for the three weights at 4 and 6.5 seconds.

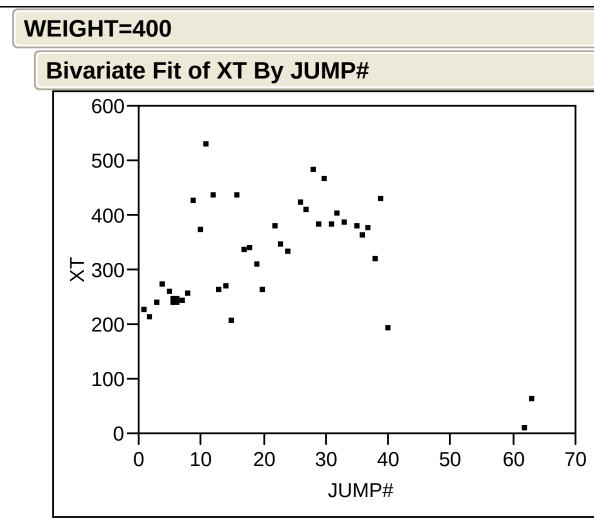
The data was studied to see if there exists some kind of linear relationship between jump number and distance by drawing a linear fit about the data. If the slope of that line is something other than zero, then a linear relationship exists. If the slope of this line is different than zero, calculations will yield a low P-value (lower than 0.05 for 95% confidence). For ease of summarizing, this analysis will only report P-values for those linear fits deemed significant (not zero), all others are considered to have no linear relationship. For longitudinal position, we only see a P-value of 0.0001 for 360K at both 4 and 6.5 seconds. One issue that is still unclear is whether the same flight test discipline was practiced for all flight tests. The 360K data was executed as a long series of jumps, without refueling between jumps. For the 400K data, 4 separate flights were made and it is unclear if the aircraft was refueled in between. There are no notes on how the 385K jumps were executed. Because of this, it is impossible to conclude that the fuel weight burned during a typical flight would cause bias in the distance of the jump.

| 4 Sec | 6.5 Sec |
| --- | --- |




Remarks: Only at 360Kwas there a statistically significant linear relationship between jump order and lateral distance. At 385K and 400K the sequence plots do appear random and regression analysis showed no significant linear relationships. Also, 400K data had about 21 jumps without data at 6.5 seconds.

**Figure 22. Sequence plots for Xt at 385K and 400K**

Figures 23 and 24 represent the same analysis for lateral position performed for 4 and 6.5 seconds. Data appears random and evenly distributed. This analysis showed no apparent relationships between lateral position and jump sequence. The sequence plots are shown, but none had a linear fit with a slope other than zero. This result indicates no lateral effect caused by weight fluctuations within a particular flight test. Since the results were not significant, no additional data about the statistical tests or calculations is presented.

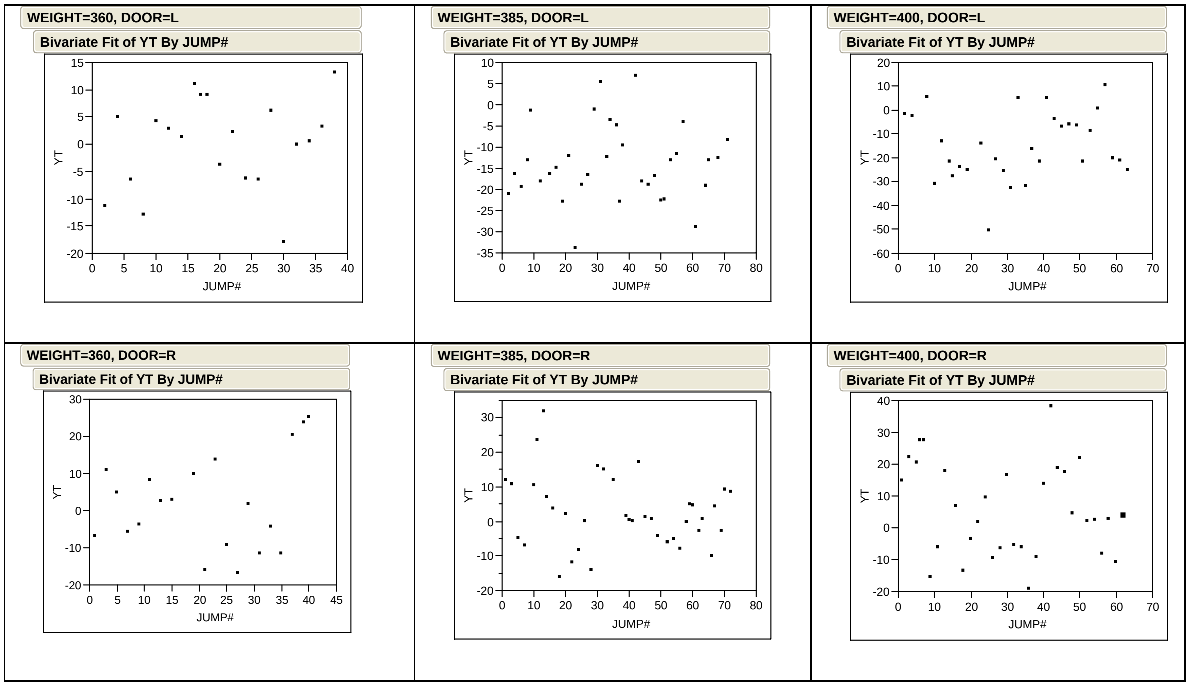



**Figure 23. Sequence plots of Yt at 4 seconds.**

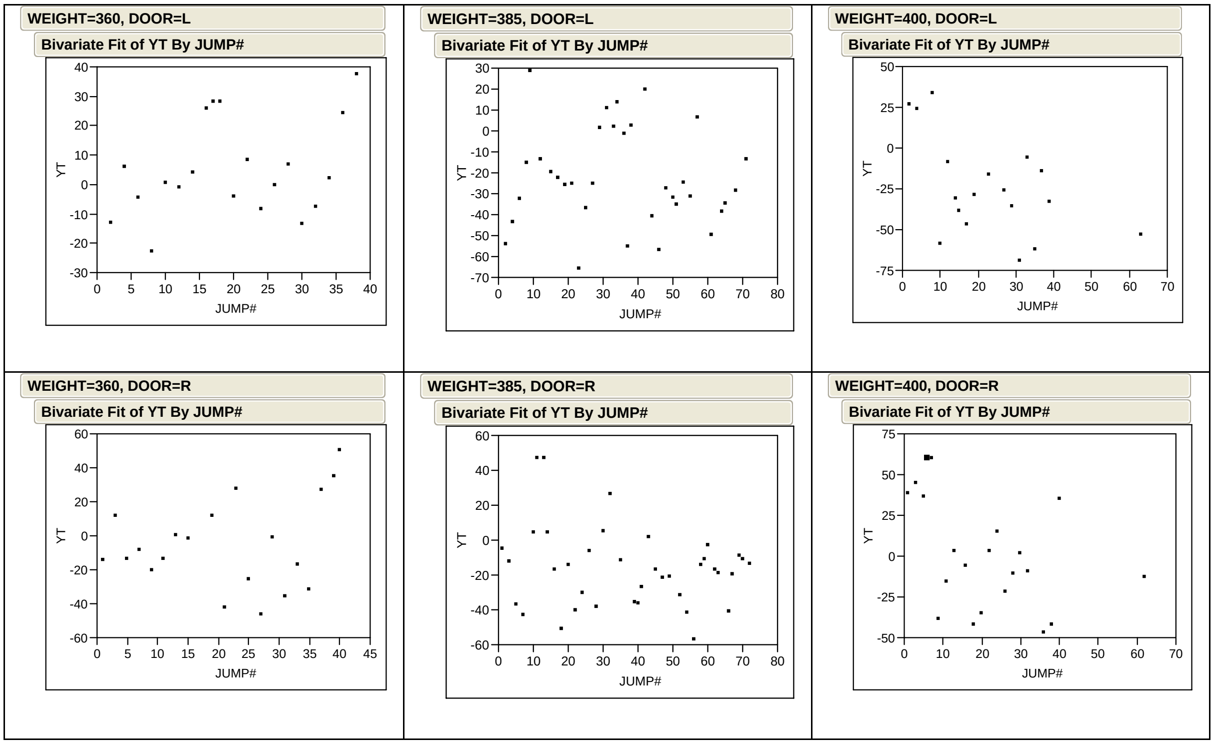



**Figure 24. Sequence plots for Yt at 6.5 seconds.**

## Summary

Position Trends in longitudinal direction ($X_t$) – There is statistical evidence of an inversely proportional relationship between weight and $X_t$. The jumps at lighter weights are consistently longer downrange than the heavier weights. What is unclear is the reason for this phenomenon and care must be taken when making conclusions about it. Analysis of variance verified the difference in means with statistical significance.

Position Trends in lateral direction ($Y_t$) – Refer back to trend plots in Figures 10 through 13 for reference. At 360K, the lateral position exhibited a symmetrical centerlining trend, where jumpers from a given side would exit the aircraft and drift towards the centerline, and cross over to the opposite side. There was a cross over point at about 4 seconds after the jump where jumpers converged to the centerline. This trend appeared for jumpers on both sides of the fuselage. The trends at 385K and 400K were much different. Both sets of jumps showed a trend to push the mean lateral position of ALL jumpers to the left of the centerline. At 385K the right side jumpers were pushed to the left, across the centerline, and continued to the left side, but the left side jumpers continued moving further left, and maintaining separation from the opposite side jumper trajectories. There was a slight convergence between the left and right door traces later in the envelope, but at this point jumpers can begin assuming some form of directional control. At 400K the same bias to the left is shown, and the separation between the left and right door traces is even greater. This certainly explains why there is such a great improvement when comparing the CDFs at the higher weights, since the jumpers tend to stay separated. Analysis of variance at 4 seconds showed significant separation for both 385K and 400K. At 6.5 seconds, the ANOVA only yielded significant separation at 400K.

Position Trends in vertical direction ($Z_t$) – The assumption made in the original methodology for minimum separation distance was valid. It appears that the altitude of jumpers varies very little with increases in weight or side of aircraft. For distance calculations between jumpers, it is reasonable to exclude the vertical component. It appears that no force other than gravity is having an effect on jumper descent rates.

Variance of position data – In all cases, for weight or door, the only inference that can be drawn from the data is that the variance increases over time. For a given jump, the first three seconds show fairly low variance, but as the parachute inflates and the jumper goes from horizontal to vertical, other forces begin to influence the trajectory, and it becomes less predictable.

Time Dependence of longitudinal direction – Downrange distance from the jump point demonstrated a significant linear relationship. Jumps occurring earlier in the flight for 360K lbs were yielding much longer $X_t$ distances than those at the end. This trend was not present in 385K or 400K, but no information is available detailing if the aircraft in those test jumps landed and refueled between sets of jumpers. Lacking this information, it is impossible to judge what would cause this linear relationship, which is contradictory to the trend analysis finding that heavier aircraft yield shorter distances.

Time Dependence of lateral direction – No significant linear relationship was seen in lateral distance. Data appeared randomly and evenly distributed about some mean.

Since minimum separation distances were calculated as a vector sum of both longitudinal and lateral position, time dependence in only one direction may be enough to cause significant differences between early and late jumps. As a result, there is no final assessment as to the validity of assumption that there is an equal likelihood of pairing any given jump, with all jumps from the opposite door, regardless of order. This would require further research into specific test procedure and flight test protocol which are unavailable at this time.

# V. Recommendations

## Significance of Research

All along, this project was about gaining insight more than certifying a jump platform. Data had already been processed yielding CDFs which conventional wisdom agreed were appropriate measures of merit. The intent here was to investigate the cause of the differences seen in the curves, and to ensure the validity of some of the original assumptions used in the analysis. While this is an academic project within AFIT, the primary customer for this information is still the C-17 SPO and in the end, these results should spring further avenues of research and review for their previous and future test flights.

## Recommendations for Action

Adding to the methodology – While the original minimum separation methodology is sound, care should be taken with the assumptions required. In particular, the assumption that any given jump can be paired with all opposite side jumps may be too optimistic. Considering the aircraft could have burned 30,000 lbs of fuel between first and last jump, pairing the first jump with the last opposite side jump may lead to larger minimum separation distances, which may “pad” the CDF. Unless there is certainty that aircraft weight changes are negligible during a test flight, assigning equal probability to the likelihood of pairing any two jumps, regardless of order, may be invalid. Analysis of time dependence should be accomplished on the actual separation distances with respect to time, then check for a linear relationship between time and separation distances. Another useful data point is if the minimum separation distances happen at a particular time step. Is one particular part of the envelope any more critical than others in terms of collision risk? The same exploratory analysis techniques used in this project should be added to the original methodology. The techniques may help in gaining some idea of what the behavior of the data is reflecting before making inappropriate assumptions which may skew results.

Brief the experts – Take this information on the road. This project focused on how the data behaved, but not why. C-17 SPO should use this information and disseminate among its subject matter experts in order to explore the true cause of the deviations witnessed here. Someone should have an idea what may be causing this and future experiments may focus on validating such hypotheses.

**Recommendations for Future Research**

Aerodynamic flow research – The data may already exist or computer models are available which can generate visual representations of the airflow around the fuselage, at the different configurations. Wind tunnel testing is also appropriate but much more expensive and may not be required. Regardless of the method, some form of effort should go into researching and characterizing the airflows influencing jumper trajectory.

Unintended consequences – A tactical evaluation of jumper trajectory should be made if the C-17 is certified up to 400K. While the tendency to push to the left may be safer with respect to collisions, it may be a dangerous condition for formation airdrops with adjacent aircraft. What are the tactical implications of a “stick” of jumpers landing far from the centerline?

Time dependence through the envelope – The current time dependence analysis was restricted to the critical points at 4 and 6.5 seconds. These points are assumed to constitute the initial chute deployment and inflation and the jumper first vertical, respectively. With such changes in jumper trajectory, these points may change in time and position. The trajectories and trends should be studied by the subject matter experts to identify if there is a change to these critical points.

Window Analysis – a technique known as window analysis can be implemented into the methodology for deriving the minimum separation CDFs. This technique is used when there are steady trends in time dependent data, but allows for comparison from one interval to the next, while minimizing the steady trends inherent in the data. In this case, instead of pairing every jump with all possible opposite side jumps, only compare to jumps just before or just after in order. For example, jump #5 (left door) would only be paired with jump #4 and Jump #6 (both from right door). The disadvantage is that a smaller sample size would be used in creating the CDF, but that can be alleviated by expanding the envelope to two or three jumps before and after, while minimizing the bias caused by time (Bowlin, 2001).

Trajectory visualization – It should be fairly simple to develop a visualization tool that allows for three-dimensional viewing the trajectories in order. Such a tool may be useful during the initial look at the data to gain insight into the time dependence of trajectories, and any obvious trends. It can also be used to visually confirm data sign convention and corrupted, inconsistent, or outlying data. There has been some prior work at AFIT which produced a visualization tool for the wingip vortices and the jumper trajectories (Harrison, 1999). Modifications to this could provide a tool to import actual data for the trajectories.

**Summary**

The trends discovered by this analysis appear to support expansion of the C-17 envelope into higher weights, by reducing the risk of jumper collision. However, that certification should be supported by a follow-on study focusing on the cause of the left bias at higher weights. Also, some form of visualization tool should be developed to help in identifying trends and tendencies which may lead to more or less collisions. In the end, the analyst should not rely solely on the output of the CDF curves to make such an assessment.

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## Vita

Major Waldemar Barnes was born 18 December 1968, in Ramey Air Force Base, Puerto Rico. He graduated from Antilles High School, Ft Buchanan, Puerto Rico, in 1986. He was selected to attend the U.S. Air Force Academy Preparatory School in 1986-1987. He attended the Air Force Academy where he graduated in 1991 with a Bachelor's Degree in Applied Mathematics. He also obtained a Master of Science Degree in Operations Management from the University of Arkansas. Maj Barnes has spent most of his career as a scientific analyst, holding positions as a flight test analyst in Air Combat Command and Air Force Special Operations Command. He also held assignments in the Air Force Agency for Modeling and Simulation and the Warrior Preparation Center. Maj Barnes now serves as a graduate student of operational sciences at the Air Force Institute of Technology, Wright Patterson AFB, OH.

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**14. ABSTRACT**

The C-17's widebody design creates concern over its tendency to "centerline" paratroopers as they exit. This effect increases the probability of collision between jumpers from opposite sides of the aircraft. Previous work has been accomplished based on calculating the separation distance between trajectories and creating cumulative distributions of separation distances. This project focuses its analysis on the trajectories and any trends that can be seen over time, based on changing aircraft gross weight. The trajectories are also analyzed for time dependence. In the end, new insight is gained into the behavior of the trajectories and can supplement previous efforts with additional methodology.

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